

Exploring surface interactions with atom chips

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We review the current status of the field of atom-surface interactions, with an emphasis on the regimes specific to atom chips. Recent developments in theory and experiment are highlighted. In particular, atom-surface interactions define physical limits for miniaturization and coherent operation. This implies constraints for applications in quantum information processing or matter wave interferometry. We focus on atom-surface interaction potentials induced by vacuum fluctuations (Van der Waals and Casimir-Polder forces), and on transitions between atomic quantum states that are induced by thermally excited magnetic near fields. Open questions and current challenges are sketched.

I. INTRODUCTION

Atom chips provide a unique and intriguing environment to study atom surface interactions. Two aspects can be identified: on the one hand, surface structures on the micron and sub-micron scale are crucially needed to produce electromagnetic fields that are patterned on this scale; this would not be possible in free space even with diffractive optics techniques, for example, given that the relevant wavelengths are much larger. On the other hand, the chip surface is a macroscopic, typically ‘hot’, object whose thermal fluctuations perturb the ultracold atoms trapped nearby. In addition, neutral atoms are typically attracted to a surface by dispersion forces of the London-Van der Waals(-Casimir-Polder) type; this can be overcome, in some range of distances, by ‘coating’ the surface with electromagnetic fields that provide a repulsive potential. Ultimately, atom chip traps are metastable: the atoms are lost when they thermalize due to fluctuating near fields or tunnel through the repulsive potential to the surface. If a coherent operation is aimed at, for example in quantum information processing, then the main goal is to increase the corresponding time scales (trap lifetime, tunnelling time). This often requires a compromise with the trend towards miniaturization because the coupling to the thermal surface is stronger at short distance.

In this report, we review the current status of the field of atom-surface interactions, with an emphasis on the regimes specific to atom chips. Recent developments in theory and experiment are highlighted. Atom-surface interactions frequently define limits in terms of a minimum height of the atom trap or a maximum time scale for coherent operation. This implies constraints for applications in quantum information processing or matter wave interferometry. Finally, open questions and current challenges are sketched.

II. MINIATURIZED HYBRID ATOM-SURFACE TRAPS

To exploit exceptionally long coherence times, atoms have to be trapped in *vacuo*. Inhomogeneous electromagnetic fields provide such traps, e.g. focused, off-resonant laser beams or static magnetic quadrupole fields (Grimm *et al.*, 2000; Hinds and Hughes, 1999). The feature size of these traps is limited by the laser wavelength or the size of the magnetic coils. Multiple, interconnected optical traps can be achieved with micro-lenses or diffractive optics (Dumke *et al.*, 2002a,b; Houde *et al.*, 2000). Miniaturization below the micron scale requires using the electromagnetic *near field* of a nanostructured surface. A large variety of trapping potentials can be achieved with a network of wires and electrodes (Schmiedmayer, 1998; Weinstein and Libbrecht, 1995), leading to the concept of the ‘atom chip’ (Folman *et al.*, 2002; Fortágh *et al.*, 2004; Reichel, 2002; Reichel *et al.*, 2001). The atoms are only indirectly coupled to the chip surface in so far as they interact with its near field. This approach combines versatility, massive parallelism, and miniaturization with quantum coherence times that are still excellent.

Atoms are neutral and couple to the field via their electric and magnetic dipole moments. Higher multipoles are typically neglected by making the long-wavelength approximation which is justified for transition frequencies that range from the kHz (trap vibration) via the GHz (hyperfine states) to the optical range (laser manipulation). More precisely, one also has to require that the near field gradients are not too large: this is the case if the typical distances between trap and chip surface are large compared to the atomic size. In this ‘nanometer window’, the chemical physics related to the transfer of electrons to the surface can be ignored, and electromagnetic couplings dominate.

It is often the case that the chip fields are small compared to the fields inside the atom so that perturbation theory is sufficient to determine the trapping potential. A more refined calculation is needed when the atomic level shifts become comparable to the hyperfine splittings, for example in strongly confining magnetic traps.

For an atom at rest placed in static magnetic or electric fields, one gets effective Hamiltonians of the form

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(Folman *et al.*, 2002; Grimm *et al.*, 2000)

$$V_{\text{mag}}(\mathbf{r}) = -\boldsymbol{\mu} \cdot \mathbf{B}(\mathbf{r}), \quad V_{\text{pol}}(\mathbf{r}) = -\frac{\alpha(0)}{2} \mathbf{E}^2(\mathbf{r}) \quad (1)$$

where \mathbf{r} is the atomic position, $\boldsymbol{\mu}$ the magnetic moment, and $\alpha(0)$ the static electric polarizability. Note that due to parity conservation, atoms do not naturally have a permanent electric dipole moment. One gets energy level shifts by diagonalizing these Hamiltonians in a subspace of atomic quantum states in the ground state manifold.

For the alkali atoms that are typically used in atom chips, the ground state is split in two hyperfine components, with a splitting in the GHz range. The magnetic interaction V_{mag} splits each hyperfine component into magnetic sublevels that get separated by the Larmor energy $\hbar\omega_L \equiv \mu_{\text{eff}}|\mathbf{B}|$ where μ_{eff} is the effective magnetic moment. (This linear Zeeman effect applies when $\hbar\omega_L$ is small compared to the hyperfine splitting.) It follows that the energy levels in a magnetic field are proportional to the magnetic quantum number m :

$$V_{\text{mag}}(\mathbf{r}) = -\mu_{\text{eff}}m|\mathbf{B}(\mathbf{r})|. \quad (2)$$

Roughly one half of the sublevels can be trapped around a minimum of the magnetic field ('weak field seekers' with $\mu_{\text{eff}}m < 0$) as long as the quantum number m is conserved (the magnetic moment follows adiabatically). A typical example for such a magnetic trap is a magnetic quadrupole that can be formed by superimposing an homogeneous ('bias') field with the azimuthal field of a linear current (in a wire written onto the chip substrate). The field minimum is located in a line above the wire and provides a linear guide for atoms ('side guide') (Denschlag *et al.*, 1998; Fortagh *et al.*, 1998). The stability limits of the adiabatic approximation are discussed by (Fortágh *et al.*, 2004; Sukumar and Brink, 1997): the loss rate shows a typical exponential suppression as the ratio of Larmor splitting to trap oscillation frequency increases.

The level shifts from the DC Stark shift Hamiltonian V_{pol} are the same for all magnetic sublevels of a given hyperfine manifold because the electronic ground state has zero orbital angular momentum and the polarizability α reduces to a scalar. They thus provide a state-independent trapping potential, and this has advantages regarding sublevel-changing collisions. The minimum energy, however, occurs at large field strength and hence on the chip surface (note that $\alpha(0) > 0$). Stable electrostatic trapping thus requires additional interactions (magnetic, optical) to 'shield' the surface (Folman *et al.*, 2002; Schmiedmayer, 1998). For example, on a chip with a side guide above a wire, additional potential minima can be created using nearby electrodes with opposite charges (Krüger *et al.*, 2003).

For time-dependent fields, one is often interested in an effective Hamiltonian that governs the atom center of mass motion on slower time scales. For optical fields, a time-average of the electric dipole interaction leads to (i) the so-called dipole potential, proportional to the light intensity and the atomic polarizability at the optical frequency (Grimm *et al.*,

2000), and (ii) to the radiation pressure force, proportional to the field's phase gradient (Dalibard and Cohen-Tannoudji, 1985; Shimizu and Sasada, 1998). A magnetic analogue can be realized with microwave fields, the potential being proportional to the microwave power and the magnetic polarizability (Spreeuw *et al.*, 1994). In both cases, the atom remains in its ground state ("dressed" by the field) if the radiation is sufficiently far detuned from the optical or microwave transition. The frequency dependence leads to a key feature of the dipole potentials: if the time-dependent field drives the atom below (above) the resonance frequency, the atom is attracted to (repelled from) the field maxima, respectively. This allows to build state-independent traps with a 'red-detuned' optical field pattern (Birkel *et al.*, 2001) or a focused laser beam ('optical tweezer', see, e.g. Chikkatur *et al.* (2002)). Microwave pulses can also be used to imprint phase shifts on the atomic wave function with state-dependent signs, realizing one of the building blocks for qubit processing.

To summarize, the trapping potentials in atom chips are determined by diagonalizing the interaction of the atomic dipole moments with the chip fields. The eigenvalues can be used as potentials if the atoms move sufficiently slowly. This is generally the case for typical ultracold temperatures and trap depths. Magnetic fields provide potentials that depend on the magnetic quantum number, while electric fields give state-independent traps. In the following sections, we apply perturbation theory to the eigenstates in the trapping fields to describe the interaction with the surface. This leads to induced level shifts due to both vacuum and thermal fluctuations (Sec.III) and transitions induced between the atomic quantum states (Sec.IV).

In the context of miniaturized atom traps, we select as follows further directions of interest:

- (a) wire and field configurations that optimize the flexibility of trapping and guiding potentials (Günther *et al.*, 2005a; Hommelhoff *et al.*, 2005);
- (b) non-metallic hybrid chips with magnetized structures (Barb *et al.*, 2005; Jaakkola *et al.*, 2005; Vuletic *et al.*, 1998). or integrated optical components (microcavities, waveguides, photonic crystals) (Barnett *et al.*, 2000; Eriksson *et al.*, 2005; Vučković *et al.*, 2002). This may provide an environment with reduced electromagnetic noise (see Sec.IV) and facilitate single-atom detection (Horak *et al.*, 2003);
- (c) the stability of the adiabatic approximation underlying the trapping potentials in the presence of electromagnetic fluctuations (see Sec.IV);
- (d) corrections to the atomic level structure beyond the long-wavelength approximation. This is particularly important for strongly confining potentials near nanostructures where the relevant length scale, given by the structure size, is much smaller than the field wavelength. For strong magnetic quadrupole fields, see the recent papers by Lesanovsky and Schmelcher (2005); Lesanovsky *et al.* (2005);

(e) matter wave dynamics in low-dimensional guiding potentials. Ultracold atoms thus provide a setting to study mesoscopic transport, similar to electrons in miniaturized solid state structures. One advantage of atoms is that the interparticle interactions are simple to describe and can be controlled experimentally. For the impact of interactions on resonant tunnelling through an atomic quantum dot, for example, see the recent paper by Paul *et al.* (2005).

A topical issue of The European Physical Journal D () has recently been devoted to atom chips, reporting recent advances in the field with contributions from both theory and experiment. Papers directly related to atom-surface interactions have been contributed by Buhmann *et al.* (2005); Dikovskiy *et al.* (2005); Henkel (2005a); Kallush *et al.* (2005); Lesanovsky and Schmelcher (2005); Zhang *et al.* (2005); some of them are summarized below.

III. SURFACE INTERACTION POTENTIALS

A. Introduction

An atom in front of a surface is a well-known, paradigmatic situation for cavity quantum electrodynamics (cavity QED) (Haroche, 1992; Hinds, 1994). The presence of the surface introduces a distance-dependent contribution to the Lamb shift, the displacement of atomic energy levels due to virtual transitions induced by the electromagnetic vacuum (i.e., the field's zero point fluctuations). This energy shift is called the Van der Waals-London or Casimir-Polder potential, depending on the relative magnitude of the atom-surface distance compared to typical atomic transition wavelengths. The same names are also attached to the interaction between two neutral atoms that can be attributed to their electric dipole (quantum) fluctuations and the vacuum field.

For the alkali atoms, the electric dipole fluctuations in the ground state $|g\rangle$ are dominated by virtual transitions to the first excited state $|e\rangle$ (the D1 and D2 lines). The Van der Waals-London limit applies at atom-surface distances much smaller than the corresponding wavelength, $z \ll \lambda_{eg}$. The potential is then dominated by the instantaneous (non-retarded) response of the surface to the electric dipole fluctuations and can be interpreted in terms of an image dipole. One finds an energy shift proportional to the squared electric dipole matrix elements $|\langle g|d_i|e\rangle|^2$, with a power law $1/z^3$ and a frequency average of the surface 'reflectivity' in the non-retarded limit, weighted by the atomic polarizability (Wylie and Sipe, 1984)

$$E_{vdW}(z) = -\frac{1}{2\pi\epsilon_0(2z)^3} \sum_e (|\langle g|d|e\rangle|^2 + |\langle g|d_z|e\rangle|^2) \times \text{Im} \int_0^\infty \frac{d\omega}{2\pi} \frac{\epsilon(\omega) - 1}{\epsilon(\omega) + 1} \frac{\omega_{eg}}{\omega_{eg}^2 - \omega^2 - 0i\omega}, \quad (3)$$

where $\epsilon(\omega)$ is the dielectric function of the surface material. The summation runs over all excited states that are connected

with electric dipole transitions to the ground state; taking only the D1/D2 transitions gives results accurate within the percent level (Caride *et al.*, 2005).

In the opposite regime, $\lambda_{eg} \ll z$, retardation reduces the size of the interaction, and one gets the $1/z^4$ Casimir-Polder shift. Its expression involves atomic polarizability and surface dielectric function at zero frequency, with an angular average of surface reflection coefficients

$$V_{CP}(z) = -\frac{3c}{4\pi^2\epsilon_0(2z)^4} \sum_e \frac{\langle g|d_i|e\rangle\langle e|d_j|g\rangle}{\omega_{eg}} \times \int_0^{\pi/2} d\alpha \sin\alpha \left\{ -\cos^2\alpha \Delta_{ij} r_s(\epsilon_{stat}) + (2\sin^2\alpha \delta_{iz}\delta_{jz} + \Delta_{ij}) r_p(\epsilon_{stat}) \right\}, \quad (4)$$

$$r_s(\epsilon_{stat}) = \frac{1 - \sqrt{\epsilon_{stat} \cos^2\alpha + \sin^2\alpha}}{1 + \sqrt{\epsilon_{stat} \cos^2\alpha + \sin^2\alpha}}, \quad (5)$$

$$r_p(\epsilon_{stat}) = \frac{\epsilon_{stat} - \sqrt{\epsilon_{stat} \cos^2\alpha + \sin^2\alpha}}{\epsilon_{stat} + \sqrt{\epsilon_{stat} \cos^2\alpha + \sin^2\alpha}}. \quad (6)$$

This formula can be derived from the results of Wylie and Sipe (1984). We have denoted $\Delta_{ij} = \delta_{ij} - \delta_{iz}\delta_{jz}$. For a perfect conductor and more generally for metals with a nonzero DC conductivity, $\epsilon_{stat} = i\infty$, and therefore $r_s \equiv -1$ and $r_p \equiv +1$. In that case, the α -integral in Eq.(4) gives $\frac{4}{3}\delta_{ij}$. For an explicit formula for all ϵ_{stat} , see Antezza *et al.* (2004).

Note that formulas (3, 4) apply, strictly speaking, at zero temperature only. For $T > 0$, thermal photons must be taken into account by including a factor $\coth(\hbar\omega/2k_BT)$ in the ω -integral (3) and by adding a term involving the surface reflectivity at the transition frequency ω_{eg} . This enhances the contribution of low-lying substrate resonances (Section III.B.3). The asymptotic expansion behind (4) is only valid for distances $z \ll \hbar c/k_BT$. For larger distances (beyond a few μm at room temperature), one finds an energy shift scaling like T/z^3 (Barton, 1997).

Analytical expressions for the Van der Waals-London-Casimir-Polder interaction are restricted to simple geometries (planar surface or cavity, cylinder, sphere), while one faces a difficult computational problem in a generic atom chip geometry. This is related to the double integration over both frequencies and 'angles of incidence'. In the nonretarded limit (Van der Waals-London force), the surface response can be computed from electrostatics, using $\epsilon(\omega)$ as dielectric constant. The frequency integration in Eq.(3) remains to be done, however, and is not restricted in general to a narrow range. And the result is of limited use for typical atom chips: with distances of a few microns, one is right in the transition regime to the Casimir-Polder potential where retardation comes into play.

B. Recent developments

1. Theory

A large number of papers have appeared in recent years that refine the QED of atom-surface forces. Prominent trends include the impact of finite temperature (the previous formulas are restricted to $T = 0$), and realistic models for the surface material. Non-equilibrium situations and the consequences for Bose-Einstein condensates trapped near a surface have been considered very recently. A selection is listed in the following.

Barton has given a straightforward extension of the standard field mode expansion to finite temperature and a planar cavity between two lossy surfaces (Barton, 1997).

Boustimi *et al.* (2002, 2003) have considered the cylindrical geometry of a nanowire, taking into account the metal's non-local dielectric function. Applications mainly focus on scattering and interferometry with thermal atomic beams. Nha and Jhe (1997) cover a similar geometry and focus on atom and molecule spectroscopy.

Klimchitskaya and co-workers have used accurate data for frequency-dependent atomic polarizabilities and the material dielectric functions to demonstrate significant deviations in the Van der Waals-London regime compared to the contribution of the D1/D2 lines (Babb *et al.*, 2004; Caride *et al.*, 2005). Asymptotic formulas are given and shown to be accurate to within one percent.

Côté, Segev, and co-workers have investigated the interaction of atoms and molecules with metallic and dielectric surfaces, with a particular emphasis on surfaces coated by evanescent light fields and on ultraslow matter wave reflection ('quantum reflection') from the attractive interaction potential (Côté *et al.*, 1997; Segev *et al.*, 1997). Doak and Chizmeshya (2000) have discussed the scaling behaviour of quantum reflection and pointed out the effect of a near-threshold resonance state. Delay times in quantum reflection have been computed recently; they allow to define an 'effective mirror position' where the matter wave is bouncing off the potential (Friedrich and Jurisch, 2004; Jurisch and Friedrich, 2004). For a review, see Kallush *et al.* (2005); recent experiments on quantum reflection are described in Section III.B.2 below.

Buhmann and co-workers have applied a quantization scheme for absorbing and dispersive media to derive expressions for atom-surface interactions that cover also magneto-dielectrics (Buhmann *et al.*, 2005, 2004a,b). The impact of the surface is encoded in the backscattering of the radiation of an electric point dipole (i.e., reflection coefficients in the Green tensor). In addition, the atomic polarizability becomes 'dressed' by the surface, leading to higher order corrections that do not take the simple form of a potential gradient.

Antezza *et al.* (2004) have shown that at a distance of a few microns, the interaction of surface at finite temperature with a condensate can shift the elementary excitations of the latter. Although the surface interaction is quite weak in this

range, the effect is experimentally accessible with high precision spectroscopy of the condensate motion, as reported by Harber *et al.* (2005); McGuirk *et al.* (2004). The accuracy reached is sufficient to detect the thermal T/z^3 regime with surface heated above room temperature.

The same theory we outlined above can also be used for sub-wavelength particles, as long as higher multipole remain negligible. In this context, non-equilibrium forces have been studied recently. Possibly repulsive or non-conservative forces are generic features in this context (Linder, 1966). Forces between nanoparticles at different temperatures have been computed by Cohen and Mukamel (2003). The interaction with finite-temperature surfaces has been studied, paying attention to dissipation for a moving particle (Volokitin and Persson, 2002), repulsion from radiation pressure (Henkel *et al.*, 2002), coupling to magneto-dielectric surfaces (Buhmann *et al.*, 2004a), and unusual power laws at large distance (Antezza *et al.*, 2005).

An example where atom-surface interactions are used as a probe for condensed matter physics is the work by Horing (2004). He has considered the modification of the Van der Waals potential when a strong magnetic field is applied to a metallic surface and forces its electrons on Landau orbits.

Finally, fluctuations of the Van der Waals force have been addressed by Wu *et al.* (2002), following similar work by Barton (1991a,b) on vacuum fluctuation forces between surfaces (the Casimir force). Force fluctuations for a nanoparticle have been considered by Zurita-Sánchez *et al.* (2004) to derive a friction force via the fluctuation-dissipation theorem. This is a topic of relevance for coherent manipulations with atom chips, since fluctuations lead to decoherence (Section IV.D).

2. Measurements with cold atoms

In the following, we focus on a few aspects that have emerged in recent experimental measurements of surface-induced interaction potentials with cold atoms: (a) the lowering of the trap depth with an additional loss channel towards the surface; (b) the roughening, at close distance, of a magnetic atom guide due to imperfections in the chip structures; and (c) the reflection of ultracold atoms and condensates from the attractive surface potential (quantum reflection).

a. Trap depth. The atom-surface attraction can be measured by balancing it with a controllable 'electromagnetic coating', as shown with atoms reflected from an evanescent wave mirror by Landragin *et al.* (1996). The same principle has been used more recently in surface-induced evaporation experiments by Hammes *et al.* (2003). They control the barrier height to the surface and remove selectively the most energetic atoms in a trap, thus reducing the temperature down to quantum degeneracy. Quantitative measurements of atom-surface interactions in the retarded limit of a few microns are difficult to

perform, however, because they are so weak. Experiments have to carefully control electric stray fields due to surface adsorbates (Harber *et al.*, 2005; McGuirk *et al.*, 2004). Lifetime measurements in traps at different heights, performed by Lin *et al.* (2004), have given indications that surface interactions play a role at micrometer heights. Similar results have been obtained by Treutlein *et al.* (2004), where a trapped atom cloud is shifted for some time closer to the surface. The data analysis is complicated by the fact that in a magnetic trap, one has to separate the effect of the surface potential from a distance-dependent loss mechanism that is due to transitions induced by thermal magnetic fields radiated by the surface, see Section IV and the discussion by Dikovskiy *et al.* (2005).

b. Trap roughening. The wires on an atom chip substrate show imperfections on a scale of nanometers to microns, depending on the fabrication process. The process called ‘electroplating’ creates wires with stronger inhomogeneities and larger side wall roughness compared to electron beam nanolithography. The electric current in a rough wire has nonzero components perpendicular to the wire axis that create spatially inhomogeneous, non-azimuthal magnetic fields. These fields lead to a rough trapping potential when combined with a large uniform bias field. Since the trap minimum is defined by the cancellation of two large fields (wire and bias), a very small angular deviation of the wire field (10^{-4} rad) is sufficient to produce an inhomogeneous potential that fragments a cold atom cloud as the trap approaches the wire. This phenomenon has been observed by several groups (Kraft *et al.*, 2002; Leanhardt *et al.*, 2002) and its origin has been elucidated in the last few years.

Kraft *et al.* (2002) have performed careful symmetry checks to demonstrate that the fragmentation potential arises from a small, current-induced magnetic field along the wire axis. A statistical theory for rough wire edges has been worked out by Wang *et al.* (2004) to explain the quasi-periodicity observed in fragmented clouds. Estève and co-workers have measured the anomalous magnetic field component from the density distribution of a cold atom cloud and have linked that field to the current flowing along rough wire edges, as observed with electron microscopy (Estève *et al.*, 2004). The overall picture has emerged that small-scale edge roughness gives magnetic fields that decay faster with distance so that a broad maximum emerges in the spatial frequency spectrum of the trapping potential, defining a dominant roughness length scale. Wildermuth *et al.* (2005) have shown that Bose-condensed clouds provide a magnetic field sensor with unique performances in terms of field sensitivity and spatial resolution.

From the viewpoint of coherent atom processing, a rough guiding potential can be avoided with high-quality fabrication technology, for example, by writing the chip structures with a direct electron beam. But a rough guide can also be turned into a physically interesting system, by realizing disorder typical for solid-state environments. One may thus study paradigmatic problems related to superfluidity, mesoscopic transport and matter wave localization.

matic problems related to superfluidity, mesoscopic transport and matter wave localization.

c. Quantum reflection. A matter wave incident on a potential that varies rapidly on the scale of the wavelength can be reflected, with a nonzero probability, even if the potential is attractive. The same effect occurs routinely for light at an interface. First experiments with ultracold hydrogen atoms have been performed by Berkhout *et al.* (1989). Quantum reflection is related to the breakdown of the WKB or short-wavelength approximation, since the latter predicts that the matter wave follows the corresponding classical particle path. For the typical power-law potentials occurring in atom-surface interactions, the WKB approximation breaks down in a limited range of distances: there, the potential varies rapidly on a scale set by the incident kinetic energy (Côté *et al.*, 1997; Maitra and Heller, 1996; Segev *et al.*, 1997).

When the surface potential is weaker, the ‘bad lands’, where the WKB approximation fails, approach the surface and, what is more important, they become more pronounced. This has been exploited in experiments (Shimizu, 2001; Shimizu and Fujita, 2002) to enhance the efficiency of quantum reflection. The surface density of a silicon wafer has been reduced by writing a relief grating, and this improved the reflectivity for metastable neon atoms. It has been studied in detail to which extent the atom-surface interaction actually plays a role in this context (Kouznnetsov and Oberst, 2005; Oberst *et al.*, 2005a,b).

Pasquini *et al.* (2004) have demonstrated the quantum reflection of a rubidium Bose-Einstein condensate from a silicon wafer. A reasonable agreement has been found with a theory for non-interacting atoms, using a potential that interpolates between the Van der Waals and Casimir-Polder limits. Measurements of this kind, using ultracold atoms, hence provide the possibility to explore the weak long-distance tail of atom-surface interactions (Kallush *et al.*, 2005; Segev *et al.*, 1997).

3. Measurements with thermal atoms

a. Frequency shifts. The reflection of light from a thin cell filled with an atomic vapor can be used for high-precision atomic spectroscopy. The transient response of atoms that desorb from the cell interface gives a narrow spectral feature that is insensitive to Doppler broadening. It allows to infer frequency shifts of transitions to excited atomic levels, and hence the difference between the corresponding energy shifts (Barton, 1997). The impact of resonant absorption in the cell walls and of thermal occupied surface modes, at finite temperature, has been demonstrated recently by Failache *et al.* (2003). These experiment and related theoretical issues are discussed in the review paper by Bloch and Ducloy (2005).

b. Elastic and inelastic scattering. At grazing incidence, even a thermal atom beam can undergo quantum reflection, the normal velocity component becoming extremely small. This has been demonstrated experimentally by Droujinina (2003); Druzhinina and DeKieviet (2003), using clever echo techniques with a spin-polarized He3 beam. By varying the angle of incidence, both non-retarded and retarded branches of the atom-surface potential could be probed.

The Hamiltonian of the Van der Waals potential has the symmetry of electric quadrupole transitions. It thus has nonzero matrix elements between different fine structure states split by the spin-orbit interaction. In an experiment with a metastable argon atom beam, the corresponding transitions have been observed via a very weak inelastic scattered beam. The spin-orbit energy splitting is changed into kinetic energy for the motion normal to the surface, leading to a large angular deviation, as shown by Boustimi *et al.* (2001). This weak effect could only be demonstrated because of the excellent efficiency of detecting metastable atoms.

IV. SURFACE-INDUCED DISSIPATION

A. Introduction

We now turn to the transitions between atomic eigenstates in the trapping fields that are induced by the presence of the atom chip surface. The system at hand is in fact strongly out of equilibrium, the surface being typically at a much higher temperature than the atoms. The useful time scale for stable trapping and coherent manipulation is thus set by the surface-induced transition rates. In the same way as for the interaction potentials, atom chips operate in a regime where the main coupling is mediated by the electromagnetic field, more precisely, its fluctuations radiated by the surface. The dominant atomic transitions happen in the ground state manifold, between its hyperfine and Zeeman sublevels, and between the center of mass eigenstates in the trapping potential. For these transitions, field fluctuations are highly thermal, and transition rates increase linearly with temperature. The opposite situation applies to optical transitions to electronically excited states that occur in laser traps.

The sources of electromagnetic field fluctuations in atom chips can be roughly categorized as follows.

(a) Vacuum (also called zero point) fluctuations of field modes and, at lower frequencies, their thermal counterpart:

(a-1) One type of field modes are scattering states labelled by plane wave photons incident from infinity (or from the walls of the experimental setup). They give rise to a spatially modulated field pattern upon reflection from the chip structures.

(a-2) A second type of modes is provided by the radiation due to polarization charges or currents inside the chip material. These modes have to be taken into account separately when the chip material shows absorption. At sub-wavelength distances, their non-propagating near fields actually dominate

the field fluctuations and increase them orders of magnitude beyond the Planck blackbody spectrum.

(b) The fluctuations of the external currents and fields that provide the trapping potential. In a first step, they can be calculated along the same lines as the static fields that form the trap, using a linearization procedure. This works provided retardation is negligible at the relevant frequencies. Current fluctuations at the shot noise level require a more careful description of electron transport through the chip wires.

From a general perspective, ultracold atoms can be considered as sensitive detectors of the electromagnetic field close to the chip structures: trap equilibrium positions depend on the mean fields (average current, electrode charge), while transitions between states are proportional to the local spectral density of the field fluctuations.

For example, electric dipole transitions at optical frequencies happen at a rate given by Fermi's Golden Rule that can be written in the form

$$\gamma_{i \rightarrow f} = \frac{1}{\hbar^2} \sum_{k,l} \langle i | d_k | f \rangle \langle f | d_l | i \rangle S_{kl}^E(\mathbf{r}, \mathbf{r}; -\omega_{if}) \quad (7)$$

$$S_{kl}^E(\mathbf{r}, \mathbf{r}'; \omega) = \int d\tau e^{-i\omega\tau} \langle E_k(\mathbf{r}, \tau) E_l(\mathbf{r}', 0) \rangle. \quad (8)$$

Here, $|i, f\rangle$ are the initial and final states and $S_{kl}^E(\mathbf{r}, \mathbf{r}; -\omega_{if})$ is the local spectral density of the electric field. It gives the strength of field fluctuations with the transition frequency ω_{if} . It is usually identified with the local density of photon states LDOS (Barnes, 1998; Chicanne *et al.*, 2002; Colas des Francs *et al.*, 2002). Due to an asymmetry between electric and magnetic fields in the near field, this identification has to be done with care, however (Joulain *et al.*, 2003). The LDOS has also been split into radiative and nonradiative parts (Savasta *et al.*, 2004) which is similar to the distinction made above between photon scattering states and material radiation. Above a structured substrate, the decay rate $\gamma_{i \rightarrow f}(\mathbf{r})$ is position-dependent and allows to infer local optical properties with a sub-wavelength spatial resolution (Henkel and Sandoghdar, 1998; Parent *et al.*, 1999). This can be used in scanning near field microscopy, the advantage being that $\gamma_{i \rightarrow f}(\mathbf{r})$ is independent of illumination and detection conditions. Some evidence for a distance-dependent decay rate $\gamma_{i \rightarrow f}(z)$ close to a dielectric has been found by Ivanov *et al.* (2004): cold atoms dropped onto a glass surface have been detected via the absorption of an evanescent wave coating the surface.

In optical traps for ultracold atoms, the decay rate (7) determines spontaneous light scattering since the trapped atoms show some finite admixture of the electronically excited state. Spontaneous scattering ($e \rightarrow g$) is detrimental to coherent atom storage due to the random recoil momentum of the emitted photon. Its rate can be pushed to low levels (of the order of 1 s^{-1}) by operating the optical trap at very large detuning (Grimm *et al.*, 2000).

In the next Section IV.B, we focus on transitions among the ground state manifold, with the atomic center of mass position assumed to be fixed. These transitions are due to magnetic near field fluctuations that have been identified recently as the main source of loss from magnetic atom chip traps. We then switch in Section IV.C to perturbations of the quantized center of mass motion.

B. Magnetic near field noise

1. Overview and theoretical methods

In a typical magnetic trap, only a subset of Zeeman sublevels (the weak field seeking states). Magnetic dipole transitions to the non-trapped sublevels can thus be observed as atom loss. The rate of these transitions is proportional to the magnetic field spectral density $S_{kl}^B(\mathbf{r}, \mathbf{r}; -\omega_{if})$; with the transition frequency $\omega_{if}/2\pi$ being in the range $1 - 100$ MHz for typical Larmor frequencies. A general theory to compute the local magnetic noise spectrum has been given by Agarwal (1975), and Sidles *et al.* (2003) have presented a calculation scheme for metallic and superconducting structures. In the context of quantum electrodynamics, Knöll, Welsch, and co-workers have developed a consistent scheme to quantize the macroscopic Maxwell equations with dispersive and absorbing media (Knöll *et al.*, 2001). This scheme can also be used to cover the non-equilibrium case of a surface hotter than the vacuum surroundings.

a. Substrate radiation. The simplest model for the thermal fluctuations inside the substrate is based on the assumption of local thermodynamic equilibrium. The fluctuation spectrum of the thermal current density is then proportional to the mean occupation number $(\exp(\hbar\omega/k_B T(\mathbf{x})) - 1)^{-1} \approx k_B T(\mathbf{x})/\hbar\omega$, on the one hand, and $\text{Im } \varepsilon(\mathbf{x}; \omega)$, the imaginary part of the (local) dielectric function, on the other. The latter can be interpreted as the local density of states of the reservoir where excess field energy is absorbed.

Starting from this model of the thermal currents, one computes the magnetic noise spectrum by adding incoherently the radiation from all volume elements occupied by the material (Sidles *et al.*, 2003; Turchette *et al.*, 2000; Varpula and Poutanen, 1984). This approach indicates that magnetic fluctuations increase with the volume of absorbing material. A simple proportionality holds only in the magnetostatic regime, however, where damping inside the material can be neglected before the field emerges into the vacuum above. This is typically the case when either the distance of observation z or the thickness of the metallic chip structures are much smaller than the skin depth $\delta = c/(\omega \text{Im } \sqrt{\varepsilon}) \approx (\mu_0 \sigma \omega / 2)^{-1/2}$ (σ : substrate conductivity). One also has to take into account the boundary conditions for the magnetic field at the substrate-vacuum interface, otherwise magnetic field components parallel to the interface are over-estimated

by a factor of order three. If this correction is neglected, the incoherent summation over the substrate volume provides a versatile scheme that can handle arbitrary chip structures (Henkel and Pötting, 2001).

b. Equilibrium near field. A more accurate computation applies thermodynamic equilibrium statistics to the field itself, as done by Agarwal (1975); Henkel *et al.* (1999); Rekdal *et al.* (2004). The noise spectrum is then proportional to $k_B T(\mathbf{x})/\hbar\omega$ and $\text{Im } H_{ij}(\mathbf{r}, \mathbf{r}; \omega)$, the imaginary part of the magnetic Green tensor (i.e., the radiation of an oscillating point magnetic dipole). The reflection from the chip structure is needed to compute the Green tensor, which is a problem of similar complexity as in the previous approach, but no further integration is required. Reflection coefficients are straightforward to work out in simple geometries where an expansion in adapted coordinates is possible. This approach covers also distances large compared to the skin depth, but is restricted to a field in global thermodynamic equilibrium. It turns out that above a metallic surface where $\delta \ll \lambda$, electromagnetic fluctuations are dominantly magnetic if $z \leq (\delta \lambda^3)^{1/4}$ (Henkel, 2005b; Joulain *et al.*, 2003).

2. Typical scalings

Model calculations for metallic layers and wires in the magnetostatic approximation have been given by Dikovskiy *et al.* (2005); Henkel and Pötting (2001). The relevant scales are the distance z of the trap center and the skin depth δ at the transition frequency, and magnetostatics applies at short distance $z \ll \delta$. There, the magnetic noise spectrum is independent of frequency (white noise) and follows power laws as a function of distance z : above a half-space, $S^B \sim 1/z$, above a layer with thickness a , $S^B \sim a/z^2$, above a thin wire with diameter d , $S^B \sim d^2/z^3$. These power laws for the noise spectrum are completely specified by the chip geometry. One sees that the noise power decreases if the amount of metallic material is reduced.

At intermediate distances, $\lambda \gg z \gg \delta$, one finds again power laws for planar geometries, but the noise becomes colored. For a half space and a thick layer (compared to the skin depth), an exponent $1/z^4$ has been found by Henkel *et al.* (1999) so that the magnetic noise decreases faster than in the magnetostatic regime. One reason for this is that only thermal currents in a skin layer of the surface contribute, another one is the very inefficient transmission of the fields through the metallic surface (Henkel, 2005a). In this regime, a layer thinner than the skin depth even enhances the magnetic noise, as discussed by Varpula and Poutanen (1984).

The material properties enter via a prefactor proportional to the product $T\sigma$. In order of magnitude, the transition rate between magnetic states is at short distance

$$z \ll \delta : \quad \gamma_{i \rightarrow f} \approx 57 \text{s}^{-1} (T/300 \text{ K}) (\sigma/\sigma_{\text{Au}, 300 \text{ K}})$$

$$\times \sum_{kl} \frac{\mu_k \mu_l^*}{\mu_B^2} (Y_{kl}(\mathbf{r}) \times 1 \mu\text{m}) \quad (9)$$

where μ_B is the Bohr magneton, the conductivity $\sigma_{\text{Au}, 300 \text{ K}}$ for gold is taken as a reference, and $\mu_k = \langle i | \mu_k | f \rangle$ are the magnetic dipole matrix elements. The tensor $Y_{kl}(\mathbf{r})$ is determined by the chip geometry, and scales with trap distance as mentioned above. Noise reduction can be achieved by cooling with suitable alloys where $T\sigma(T)$ is not constant, see (Dikovsky *et al.*, 2005). This approach is limited to weak wire currents where Joule heating of the wires can be neglected; for more details, see the papers by Groth *et al.* (2004); Zhang *et al.* (2005). For superconducting material, the noise is contributed by the fraction of normally conducting electrons, see Scheel *et al.* (2005); Sidles *et al.* (2003).

Finally, technical current noise gives a magnetic power spectrum with a $1/z^2$ power law, since the fluctuating fields vary like $\Delta I/z$ in the non-retarded regime. In atom chip experiments by Leanhardt *et al.* (2003), this noise source dominates over thermal surface fields at distances above $\sim 100 \mu\text{m}$.

3. Recent experiments

In the last few years, experiments with atom chips and microtraps have been able to confirm quantitatively the theory outlined above. A first report of surface-induced losses from a microtrap has been given by Fortágh *et al.* (2002). A quantitative estimate was difficult due to losses during the transfer of atoms into the microtrap, as pointed out by Leanhardt *et al.* (2003). Cornell and co-workers have achieved quantitative agreement with the equilibrium theory outlined above, without free parameters. In their experiment, a quadrupole trap approaches surfaces of different material in a controlled way (Harber *et al.*, 2003). Typical surface-induced transition rates are in the range of $1 - 0.01 \text{ s}^{-1}$ at distances of $10 - 100 \mu\text{m}$ and lead to a distance-dependent, additional trap loss rate. The cross over between different power laws at $z \sim \delta$ could be seen, as well as a strong dependence on the substrate conductivity.

A cylindrical geometry was studied by Jones *et al.* (2003), using a wire with a shell structure. This experiment also showed a strong impact of technical current noise. After this had been eliminated, good agreement with theoretical modelling was found, as reported by Rekdal *et al.* (2004). The increased temperature of the wire had to be taken into account.

At extremely short distances of down to $1 \mu\text{m}$, Lin and co-workers observed deviations with respect to the theory of near field-induced loss (Lin *et al.*, 2004). These have been attributed to the Casimir-Polder interaction that distorts the trapping volume and leads to the “spilling over” of atoms onto the surface. See Zhang *et al.* (2005) for a similar measurement and Dikovsky *et al.* (2005) for an alternative calculation.

Zhang *et al.* (2005) and Sinclair *et al.* (2005) have analyzed the impact of a planar, layered chip on the trap lifetime. It has been shown both in theory and experiment that if a highly

conducting metal is deposited on a substrate with a lower conductivity, the substrate properties cancel out and the magnetic noise power essentially depends on the layer thickness and conductivity.

C. Trap heating

Typical trapped atoms have a permanent magnetic moment that makes them sensitive to magnetic field fluctuations even when no transitions between Zeeman levels are involved. This is particularly relevant at lower frequencies where the resonances of the center-of-mass motion are located. To couple different center-of-mass quantum states, spatially inhomogeneous magnetic fields are required. Typical resonance frequencies are given by the trap oscillation frequency, with values in the kHz to MHz range for the tightly confined geometries of atom chips. The main consequence is the heating of an atom sample that is initially cooled down to the trap bottom.

It turns out that the dominant source of trap heating are fluctuations in the wire currents: they change the azimuthal magnetic field and shift the location of the trap center, which is equivalent to a force. Estimates for the transition rate between the two lowest eigenstates in a one-dimensional harmonic trap have been worked out by Gehm *et al.* (1998); Henkel *et al.* (2003); Savard *et al.* (1997). This heating has been observed experimentally by Hänsel *et al.* (2001) and Jones *et al.* (2003): current supplies with parasitic noise reduce the lifetime of a Bose-Einstein condensate in a surface microtrap. Low-noise electronics and shielding resulted in significant improvements down to the level where intrinsic surface noise became detectable.

The heating due to thermal magnetic fields radiated by the surface is much smaller, the main effect being trap loss, as discussed in Section IV.B. It has been shown by Henkel *et al.* (2000, 2003) that thermal magnetic fields radiated by the surface are spatially “rough” on a scale given by the trap height. The corresponding transition rate between trap eigenstates scales with $(\Delta x/z)^2$ times the loss rate due to a magnetic sublevel change, where $\Delta x (\ll z)$ is the typical size of the quantum-mechanical trap ground state. Heating is thus masked by trap loss, unless additional noise sources become dominant.

D. Surface-induced decoherence

One of the key peculiarities of quantum mechanics are linear superpositions of quantum states. They are also at the heart of the exceptionally fast “parallelism” in quantum computers compared to classical ones. In a quantum system coupled to an environment, superpositions are destroyed because the different quantum states involved get entangled with environment states that rapidly become orthogonal (Stern *et al.*, 1990; Zurek, 1991). “Open quantum systems”, as they have been dubbed, can no longer be described by Hilbert space

vectors. One has to use (reduced) density matrices that are akin to correlation functions of state vectors and that permit to retrieve all observables pertaining to the system alone. Superpositions are characterized by density matrices with non-vanishing off-diagonal elements, also called “coherences”, if written in the basis spanned by the states involved in the superposition. Decoherence is the process in which these elements decay to zero, leading to a density matrix that can be interpreted as a mixture of the basis states, that is now weighted with classical probabilities: from being “here and there”, the system has come to be “here or there”.

a. Discrete states. A typical result of the theory of open quantum systems is that environment-induced transitions between basis states also suppress coherence. For a closed two-state system $|g\rangle, |e\rangle$, for example, the off-diagonal element of the density matrix ρ evolves like

$$\frac{d\rho_{eg}}{dt} = -\frac{i}{\hbar}\langle e|[H, \rho]|g\rangle - \frac{1}{2}(\gamma_{e\rightarrow g} + \gamma_{g\rightarrow e})\rho_{eg}, \quad (10)$$

where we can identify a “decoherence rate” $\frac{1}{2}(\gamma_{e\rightarrow g} + \gamma_{g\rightarrow e})$. If transitions to other levels occur, that rate is further increased.

Additional interactions can enhance decoherence without inducing transitions, a process called “dephasing”. An example are random fluctuations $\delta\omega_{eg}(t)$ of the transition frequency of the two-level system. They randomize the relative phase between the components of a superposition state, and the superposition gets lost after averaging. This model for an open qubit system can actually be solved analytically (Unruh, 1995). It can be used to estimate the impact of magnetic field fluctuations polarized along the static trapping field (and hence along the permanent magnetic moment of the trapped atoms). If the fluctuations have a correlation time much shorter than other experimental time scales (e.g., for white noise), an additional decay is found for off-diagonal elements of the density matrix with a rate (Folman *et al.*, 2002)

$$\gamma_{\text{deph}} = \frac{\Delta\mu^2}{2\hbar^2} S_{nn}^B(\mathbf{r}, \mathbf{r}; \omega \rightarrow 0) \quad (11)$$

where $\Delta\mu$ is the difference in the magnetic moment between the two basis states and S_{nn}^B is the noise spectrum for the field component along the static trapping field. Thermal surface noise gives from Eq.(11) a dephasing rate comparable to the rate for spin flip processes, and the same power laws apply as above. Wire current fluctuations show strongly anisotropic noise for thin wires (mainly azimuthally polarized), and give a decoherence rate scaling like $1/z^4$, as shown by Schroll *et al.* (2003).

Recent experiments by Treutlein *et al.* (2004) have exploited the suppression of dephasing between states with the same magnetic moment ($\Delta\mu \approx 0$), in order to demonstrate an atomic clock in a chip microtrap. The two states are in different hyperfine manifolds and only the small nuclear magnetic

moment distinguishes their coupling to magnetic fields. Coherent superpositions between them are created in a Ramsey-Bordé interferometer scheme. The dephasing between the states did not show any distance-dependent enhancement.

Technical noise in the wire currents and bias fields from the external electronics is likely to give the dominant contribution to dephasing because of its increase at low frequencies (see Eq.11), in particular if $1/f$ noise is present. In that limit, the noise spectrum in Eq.(11) has to be evaluated at a small cutoff frequency set by the duration of the experiment, as shown by Shnirman *et al.* (2002).

b. Integrated atom interferometry. Atom chips can test the (de)coherence of matter waves by letting different parts of a spatially delocalized state interfere. Indeed, a delocalized wave in a potential, for example, is in a continuous superposition of position states. The degree of “quantum-ness” of this wave can be characterized from the correlation or coherence function $\langle \psi^*(\mathbf{x}, t)\psi(\mathbf{x}', t) \rangle$. This quantity is related to the contrast of the interference from two fictitious slits placed at \mathbf{x} and \mathbf{x}' (Goodman, 2000). The range in $\mathbf{x} - \mathbf{x}'$ over which the correlation function decays to zero is called the correlation (or coherence) length l_{coh} . Spatial decoherence is the decrease of l_{coh} due to coupling to an environment. This involves in particular random scatterings that broaden the momentum distribution, since it can be shown that $l_{\text{coh}} \sim \hbar/\Delta p$ (Zurek, 1991).

Model calculations for cold atoms interacting with a fluctuating, rough potential indicate that the atomic coherence length is reduced to the correlation length of the potential, after a time set by the power spectrum of the fluctuations (Henkel and Pötting, 2001; Jayannavar and Kumar, 1982). These calculations are based on a semiclassical Boltzmann equation, neglecting matter wave localization. Kuklov and Birman (2000); Kuklov *et al.* (2002) have studied the decoherence of a trapped condensate that scatters non-condensed atoms and considered also spinor condensates. In the latter case, robust spin coherence can be maintained if the atom interactions do not break a $SU(2)$ symmetry. The condensate superfluidity which is due to atom-atom interactions, reduces the decoherence rate, as shown by model calculations of Henkel and Gardiner (2004). This is because condensate excitations at long wavelengths are mainly phase waves (phonons) and are inefficiently excited by a fluctuating potential.

In order to test matter wave coherence on an atom chip, an interferometer setup is the method of choice. Time-dependent schemes where a trapped cloud is split and recombined, have been suggested by Cahn *et al.* (1997); Hänsel *et al.* (2001); Hinds *et al.* (2001). Recent experiments have been reported for elongated clouds that have been split along their axial direction by Bragg diffraction (Wang *et al.*, 2005) and by a magnetic grating made from a wire array (Günther *et al.*, 2005b). Interferences after splitting in the radial direction and release into free fall have been reported with an optically created dou-

ble well (Shin *et al.*, 2004) and with the two-wire scheme on a chip by Shin *et al.* (2005). These experiments use Bose-Einstein condensates and probe the phase coherence between the two parts via the interference pattern formed when the two parts start to overlap in free fall. The relative phase can be maintained when tunnelling through the barrier is still possible, as shown by Schumm *et al.* (2005). The phase diffusion due to quantum fluctuations of the atom number difference between the two parts (Javanainen and Wilkens, 1997; Pezze *et al.*, 2004) has not been conclusively observed yet. If the barrier height exceeds the chemical potential of the condensate, Shin *et al.* (2005) observed a rapid phase randomization.

Recent calculations by Negretti and Henkel (2004) indicate that when the interferometer is closed by merging the split condensate back into a single trap, atom-atom interactions can enhance the sensitivity to a relative phase shift, in particular if a controlled π phase is imposed. The interference gets also more sensitive to potential fluctuations, however. This is related to a dynamical instability of the odd eigenstate of the condensate in the double-well potential, as discussed by Stickney and Zozulya (2002).

V. CONCLUSIONS

Recent work on miniaturized atom traps has improved our understanding of atom-surface interactions in a regime where distances are comparable or large compared to optical transition wavelengths, but small compared to hyperfine or vibrational wavelengths. The fact that cold atoms can be maintained at such small distance from a macroscopic, hot surface, highlights the weakness of the coupling via the electromagnetic field. At the same time, surface coupling determines limits for miniaturization and coherent manipulation. Strategies to circumvent these limits exist, and first experimental demonstrations have been reported, for example an integrated atom clock with “decoherence-free” hyperfine states (Treutlein *et al.*, 2004).

Experiments have probed atom-surface interactions by measuring the motion of ultracold samples or transitions between atomic sublevels in the trapping potentials. Trap loss due to thermally excited magnetic near fields is now quantitatively understood, and the origin of condensate fragmentation in atom guides has been traced back to static inhomogeneities in the microfabricated wires below. Ultracold matter wave dynamics thus has emerged as a sensitive tool to probe the surface interaction potentials. More work is required to achieve a quantitative understanding. But we can say that the precise control over the center of mass motion afforded by atom chips thus has opened new routes for atomic spectroscopy.

The next steps in atom chip development are likely to involve optimized materials and geometries for magnetic noise reduction. This should enable in the near future the experimental observation of matter wave interference. We expect to see precision measurements of surface potentials, of surface-

induced decoherence and dephasing, and of the impact of atom-atom interactions.

On the theoretical side, much work has been invested into detailed models for atom chip materials and geometries, including absorption, dispersion, and finite temperature. The unusual regimes of cavity quantum electrodynamics provided by atom chips have been identified and put to use in efficient calculations. The relevant scaling laws have been spelled out and are being used for future atom chip designs. Versatile computational schemes for magnetic near field noise calculations will be developed in the near future. The complexity of predicting the Van der Waals-Casimir-Polder potential in a generic geometry is likely to become manageable using clever approximation schemes. We also anticipate an improved understanding of mesoscopic physics by studying condensate dynamics in small-scale structures near surfaces.

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